

**Opposed-Flow Flame Spread Across Propanol Pools:
Effect of Liquid Fuel Depth**

by

Inchul Kim and William A. Sirignano

Department of Mechanical and Aerospace Engineering
University of California, Irvine
Irvine, CA 92697
e-mail: spray@uci.edu

INTRODUCTION

This computational study examines the effect of liquid fuel depth on flame spread across propanol pools with and without forced, opposed air flow. The initial pool temperature is below its closed-cup flash point temperature T_{cc} ; so the liquid fuel must be heated sufficiently to create a combustible mixture of fuel vapor before ignition and flame spread can occur. Furthermore, in order for the flame to spread, an approximate rule is that the liquid fuel surface temperature ahead of the flame must be heated above T_{cc} so that a flammable mixture just above the lean limit exists ahead of the flame. The depth of a liquid fuel pool would affect the heating of the liquid fuel pool and thus the liquid fuel surface temperature ahead of the flame.

It has been observed experimentally and numerically that, at normal gravity without forced gas-phase flow and with the initial pool temperature T_o in a range well below T_{cc} , the flame periodically accelerates and decelerates (pulsates) as it propagates. The depth of a liquid fuel pool would change this range of T_o since it would affect the heating of the pool.

PHYSICAL DESCRIPTION OF THE PROBLEM

The geometry of the two-dimensional, planar model and select gas-phase boundary conditions are shown in Figure 1. The liquid fuel (n-propanol) is in a tray of 30 cm length with a exit plate of 10 cm length. The height of the open computational domain in the gas phase is 10 cm. The igniter (2 mm length, 0.1 mm thickness) is modeled as a hot pocket of gas located $x = 1$ cm from the left edge of the liquid phase and 1 mm above the liquid surface with a temperature that increases linearly from T_o at time $t = 0$ to $1300^\circ C$ in 0.1 s following activation of the igniter. The igniter temperature remains constant until $t = 0.5$ to 1 s, after which time the igniter is deactivated. The initial temperature of the liquid and gas phases is uniform and at a value T_o that is below T_{cc} ($26^\circ C$ for n-propanol). The thermodynamic pressure is assumed to remain constant at 1 atm.

GOVERNING EQUATIONS

Laboratory coordinates are used in the solution of the governing equations with variable density and thermophysical properties and a finite-rate, one-step chemical kinetics scheme is employed (Kim *et al.*, 1998).

The conditions at the gas/liquid interface are obtained from balances of energy and mass fluxes, balance of stresses, continuity of the temperature and tangential velocity, and the assumption of negligible recession of the liquid surface. (See Schiller *et al.*, 1996.)

In order to determine the effect on flame spread of the initial profile of fuel vapor concentration before the igniter activation, we first solve the governing equations without chemical reaction as a function of time. The initial conditions for this nonreacting pre-ignition case are: $T_g = T_l = T_o$, $\vec{V}_g = \vec{V}_l = 0$, $P_{D_g} = P_{D_l} = 0$, $Y_O = Y_{O\infty}$, and $Y_F = 0$ except at $y_g = 0$; $Y_F = Y_{F,ig}$ at $y_g = 0$. By employing the results from the nonreacting pre-ignition case as initial conditions, we then solve the full governing equations with chemical reaction as a function of time.

NUMERICAL METHOD

The numerical method uses the SIMPLE algorithm (Patankar, 1980) with the SIMPLEC modification and the hybrid-differencing scheme. The gas phase and liquid phase are solved separately during a time step. Interface conditions are used for the solution of each phase. During one iteration of a time step, the dependent variables are solved sequentially. Values of c_p and ρ are updated each iteration, while other properties are updated at the end of each time step. The solution procedure and grid construction follows those by Schiller *et al.* (1996).

Results were obtained with a 132×82 gas-phase grid and a 132×32 liquid-phase grid for $H_l = 2$ mm and a 132×52 liquid-phase grid for $H_l = 10$ mm with a 0.4 ms time step. Tests for dependency on grid size and time step for planar configurations revealed that there is no appreciable difference in results when the mesh size or the time step is decreased by a factor of 2.

RESULTS AND DISCUSSION

Nonreacting Pre-ignition Case

The initial profile of fuel vapor concentration in the gas phase before the igniter is activated (and thus before the chemical reaction occurs) is important because it determines the chemical reaction rate soon after flame spread begins. This profile is investigated as a function of time after filling the fuel tray both for normal gravity ($1-g_o$) and zero-gravity ($0-g_o$).

Kim *et al.* (1998) showed that, without forced air flow ($U_{opp} = 0$) at $1-g_o$, the propanol evaporates into the gas phase, and then the mixture of propanol and air flows out of the tray since propanol (and the propanol/air mixture) is heavier than the air. The air flows down to the tray to satisfy mass conservation, and a steady vapor-concentration boundary layer is established at $t = 10$ s after filling the fuel tray. Unlike the $1-g_o$ case, the $0-g_o$ case shows that the propanol vapor diffuses continuously into the air, and no velocity boundary layer is established in the gas phase.

Figures 2(a) and 2(b) show the mass fraction of propanol vapor versus y for various times at $x = 0$ for $1-g_o$ and $0-g_o$, respectively, with $T_o = 21^\circ C$ and $U_{opp} = 5$ cm/s. At $1-g_o$, there is a competition between the heavy air/propanol mixture flowing out of the tray and the incoming forced air flow. Thus, it takes longer (30 s) to establish a steady vapor-concentration boundary layer than the case without forced flow. Now, at $0-g_o$, a steady vapor-concentration boundary layer is established due to the incoming forced air flow, and it takes 10 s to establish a steady boundary layer.

Figure 3 illustrates the mass fraction of propanol vapor versus y for various times at $x = 0$ for $1-g_o$ with $T_o = 21^\circ C$ and $U_{opp} = 30$ cm/s. Almost the same result as in figure 3 is obtained for $0-g_o$. With this higher velocity of forced air flow, a steady vapor-concentration boundary layer is established quickly at $t = 5$ s both for $1-g_o$ and $0-g_o$.

Chemically Reacting Case

In this section, we present and discuss the results for flame spread under forced air flow after the igniter is activated. Specifically, the effects of the depth of liquid fuel pool are examined.

Figure 4 shows the flame location versus time under forced air flow ($U_{opp} = 30$ cm/s) and normal gravity ($1-g_o$) for two different liquid depths ($H_l = 2$ mm and 10mm) with two different initial liquid temperatures ($T_o = 21^\circ C$ and $10^\circ C$). For $T_o = 21^\circ C$ (uniform spread regime), the flame spread on the deeper pool of $H_l = 10$ mm is a little faster than the flame spread on the shallow pool of $H_l = 2$ mm. On the other hand, for $T_o = 10^\circ C$ (pulsating regime), the flame spread on the deeper pool of $H_l = 10$ mm is slower than the flame spread on the shallow pool of $H_l = 2$ mm. The reason is that a long liquid preheating distance ahead of the flame is required for the liquid fuel whose initial temperature is in the

pulsating regime (Kim *et al.*, 1998), and the deeper pool requires more heat flux into the control volume in the liquid phase ahead of the flame.

Figure 5 illustrates the flame location versus time for the same parameters as in Figure 5 but for zero-gravity ($0-g_o$). For $T_o = 21^\circ C$ (uniform spread regime), the flame spreads are close to those at $1-g_o$. On the other hand, for $T_o = 10^\circ C$ (pulsating regime), the flame on the deeper pool of $H_l = 10$ mm spreads slowly for initial 3.6 sec, then spreads fast for the next 1 sec, and then spreads slowly again.

CONCLUSIONS

Effects of the depth of liquid fuel pool to flame spread under forced air flow have been examined for $1-g_o$ and $0-g_o$, where the initial pool temperature is below the closed-cup flash point temperature and the depth of the pool is 2mm and 10mm.

For the uniform spread regime, the flame spread on the deeper pool is faster than the flame spread on the shallow pool. On the other hand, for the pulsating regime, the flame spread on the deeper pool is much slower than the flame spread on the shallow pool. The reason is that long liquid preheating distance ahead of the flame is required for the liquid fuel whose initial temperature is in the pulsating regime, and the deeper pool requires more heat flux into the control volume in the liquid phase ahead of the flame.

REFERENCES

Patankar, S. V. (1980), *Numerical Heat Transfer and Fluid Flow*, McGraw-Hill, New York.
 Schiller, D. N., Ross, H. D. and Sirignano, W. A. (1996), "Computational Analysis of Flame Spread Across Alcohol Pools," *Combust. Sci. Tech.*, 118, pp. 203-255.
 Kim, I., Schiller, D. N., and Sirignano, W. A. (1998), "Axisymmetric Flame Spread over Propanol Pools in Normal and Zero Gravities," *Combustion Science and Technology*, in press.

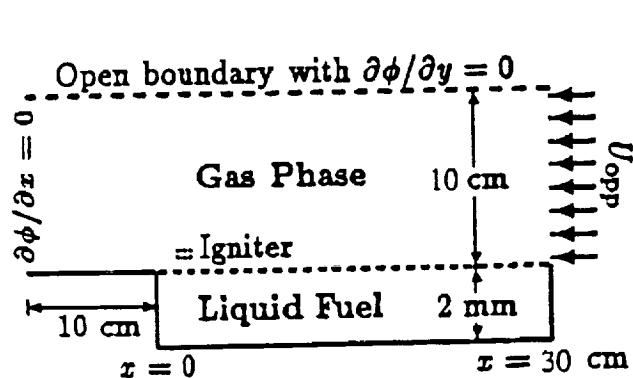


Fig. 1. Geometry and select gas-phase boundary conditions,
 where $\phi = u, v, Y_i$, or T .

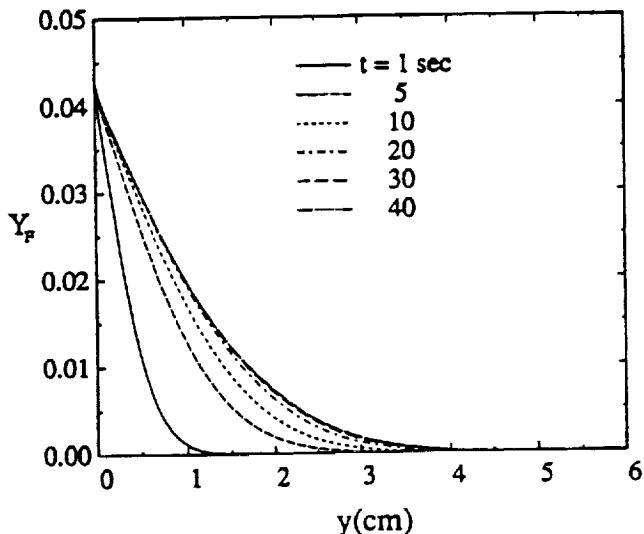


Fig. 2(a) Mass fraction of propanol vapor versus y as a function of time at $x = 0$ for $1-g_o$ with $T_o = 21^\circ C$ and $U_{app} = 5$ cm/s.

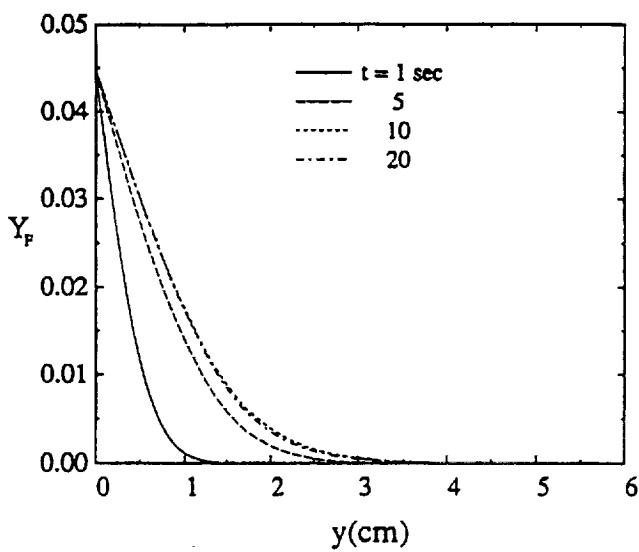


Fig. 2(b) Mass fraction of propanol vapor versus y as a function of time at $x = 0$ for $0-g_o$ with $T_o = 21^\circ C$ and $U_{opp} = 5$ cm/s.

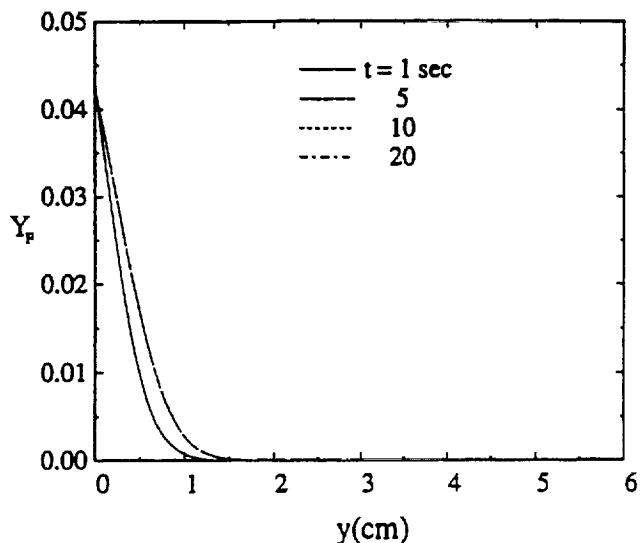


Fig. 3. Mass fraction of propanol vapor versus y as a function of time at $x = 0$ for $1-g_o$ with $T_o = 21^\circ C$ and $U_{opp} = 30$ cm/s.

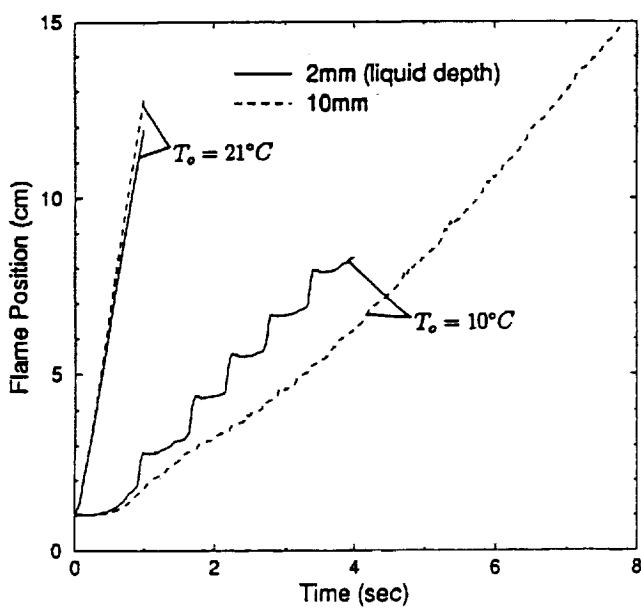


Fig. 4. Flame location versus time under $U_{opp} = 30$ cm/s and $1-g_o$ for two different H_l (2mm and 10mm) with two different T_o ($21^\circ C$ and $10^\circ C$).

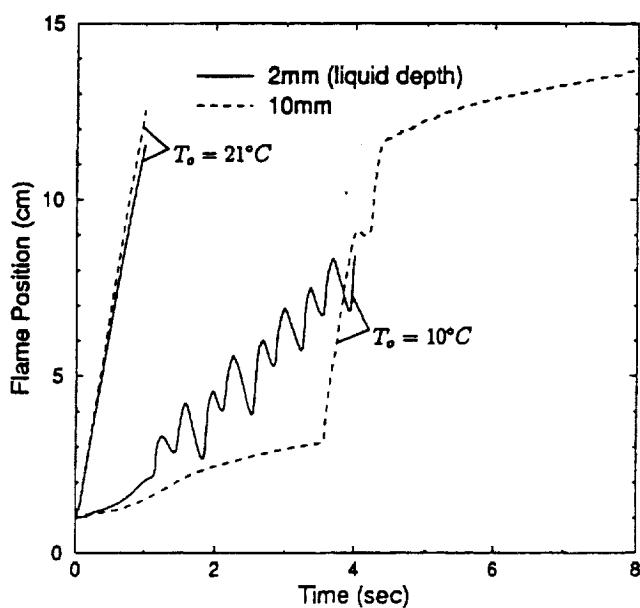


Fig. 5. Flame location versus time for the same parameters as in Figure 4 but for zero-gravity ($0-g_o$).

This report is a preprint of an article submitted to a journal for publication. Because of changes that may be made before formal publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.